LHC AND VLHC BASED *ep* COLLIDERS: *e*-LINAC VERSUS *e*-RING

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(Received December 18, 2006; revised version received January 26, 2007)

Linac-ring analogues of the LHC and VLHC based standard type *ep* collider proposals are discussed. It is shown that sufficiently high luminosities can be obtained with TESLA like linacs, whereas essential modifications are required for CLIC technology. The physics search potential of proposed ep colliders is demonstrated using pair production of heavy quarks as an example.

PACS numbers: 12.38.–t, 29.17.+w, 29.20.Dh, 29.90.+r

1. Introduction

It is known that lepton–hadron collisions have been playing a crucial role in exploration of deep inside of matter. For example, the quark–parton model was originated from investigation of electron–nucleon scattering. The HERA with $\sqrt{s_{ep}} \approx 0.3$ TeV has opened a new era in this field extending the kinematics region by two orders both in high Q^2 and small x with respect to fixed target experiments. However, the region of sufficiently small

x ($\leq 10^{-5}$) and simultaneously high Q^2 ($\geq$10 GeV^2), where saturation of parton densities should manifest itself, is not currently achievable. The investigation of physics phenomena at extreme small x but sufficiently high Q^2 is very important for understanding the nature of strong interactions at all levels from nucleus to partons. At the same time, the results from lepton–hadron colliders are necessary for adequate interpretation of physics at future hadron colliders.

Concerning LHC which hopefully will start in 2007, an $\sqrt{s} \approx 1$ TeV *ep* collider will be very useful in earlier 2010's when precision era at LHC will begin. Today, linac-ring type machines seem to be the main way to TeV scale in lepton–hadron collisions (see [1] and references therein). Construction of future linear collider or a special *e*-linac tangentially to existing (HERA, TEVATRON, RHIC) or planned (LHC, VLHC) hadron rings will provide a number of new powerful tools in addition to *ep* and *eA* options:

— TeV scale γp [2] and γA [2, 3] colliders. In this case high energy electron beam will be converted into photon beam using Compton back scattering of laser photons on ultra-relativistic electrons [4]. It should be noted that photon–hadron options cannot be realized on the base of standard (ring–ring) type electron–hadron colliders (see arguments given in [2]).

— FEL-Nucleus colliders [5]. In this case (a part of) *e*-linac will be used for production of keV energy laser beam. Let us mentioned that FEL-Nucleus colliders satisfy all requirements on ideal photon source for nuclear resonance fluorescence experiments [6].

On the other hand, there are several standard (ring–ring type) *ep* collider proposals with $\sqrt{s_{ep}} > 1$ TeV. The first one is an *ep* option for LHC [7]. This proposal, which assumes a construction of 67.3 GeV electron ring in the LHC tunnel, is considered as a part of the LHC programme in [8]. Concerning the VLHC based *ep* collider, a construction of 180 GeV *e*-ring in the VLHC tunnel is proposed in [9].

In this paper we consider linac-ring analogs of the LHC and VLHC based standard type *ep* colliders mentioned above. Two basic assumptions are made:

1. Linac and ring beams have the same electron energy;

2. Linac beam power is equal to *e*-ring synchrotron radiation power.

Main limitations on linac-ring type *ep* collider parameters are discussed in Section 2. Comparison of the LHC and VLHC based linac-ring type and standard type ep colliders is performed in Sections 3 and 4, respectively. As an example of physics search potential we consider pair production of heavy quarks ($\overline{c}$c and $\overline{b}$b) in Section 5. Comparison of the QCD-Explorer (Linac-ring type *ep* collider based on 70 GeV *e*-linac to be constructed tangentially to LHC ring) and LHeC (Large Hadron Electron Collider which assumes construction of 70 GeV *e*-ring in the LHC tunnel) proposals is represented in Section 6. Finally, we give some concluding remarks in Section 7.

2. General consideration

There are two most important collider parameters from physicist point of view, namely, center of mass energy and luminosity. The center of mass energy determines the scale of resolved dimension and achievable masses of new particles. The luminosity multiplied by corresponding cross-section determines number of available events. In addition, beam polarization, energy spread, collision frequency and luminosity per collision could be important for different phenomena.

The center of mass energy in given by $\sqrt{s}$=$2\sqrt{E_e E_p}$ for ultra-relativistic head-on colliding particles. The most transparent expression for the luminosity of linac-ring type *ep* colliders is [10]:

$$L_{ep} = \frac{1}{4\pi}\frac{P_e}{E_e}\frac{N_p}{\varepsilon_p^N}\frac{\gamma_p}{\beta_p^*} \tag{1}$$

for round, transversely matched beams with the same bunch spacing. Here, E_e is the energy of electrons, P_e is electron beam power, N_p and ε_p^N are the number of particles in proton bunch and normalized emittance of proton beam, γ_p is the Lorentz factor and β_p^* is amplitude function of proton beam at interaction point. Normalized beam emittance (ε^N) is connected to the transverse beam emittance (ε) by the relation $\varepsilon^N = \gamma\varepsilon$.

The first restrictive limitation for electron beam is beam power

$$P_e = N_e E_e n_{\mathrm{b}} f_{\mathrm{rep}}\,, \tag{2}$$

where N_e is the number of particles in electron bunch, n_{b} is the number of bunches in linac pulse and f_{rep} is repetition rate of the linac. Taking into account the acceleration efficiency, reasonable value of P_e is several tens MW.

The maximum number of electrons per bunch is determined by the beam–beam tune shift limit of the proton beam

$$\Delta Q_p = \frac{N_e r_0 \beta_p^*}{2\pi\gamma_p\sigma_{xe}(\sigma_{xe}+\sigma_{ye})}\,, \tag{3}$$

where $r_0 = 1.54 \times 10^{-18}$ m is the classical radius of proton. σ_{xe} and σ_{ye} are horizontal and vertical sizes of electron beam at interaction point. Generally accepted beam–beam tune shift value for protons in the case of ring–ring colliders is $\Delta Q_p \leq 0.003$. This limit value can be a little bit larger for linac-ring type colliders.

Disruption parameter for electrons is given by

$$D = \frac{2N_p r_e}{\gamma_e} \frac{\sigma_{zp}}{\sigma_{xp}(\sigma_{xp} + \sigma_{yp})}\,, \tag{4}$$

where r_e is the classical electron radius, σ_{zp} is proton bunch length, σ_{xp} and σ_{xy} are horizontal and vertical beam sizes of proton beam.The analysis performed for linear colliders shows that values of D up to ~ 50 are acceptable.

The most important limitation on proton beam comes from intrabeam scattering (IBS), which leads to emittance growth. We assume that IBS growth time $\tau_{\mathrm{IBS}} \geq 1$ hour is acceptable for linac-ring type colliders. For comparison, filling time is 7.5 min. and acceleration period is 1200 s for the LHC proton beam. In our calculations we use formulas from [11].

3. The LHC based *ep* collider (QCD explorer)

As mentioned above, the standard *ep* option for LHC [7] assumes a construction of 67.3 GeV e-ring in the LHC tunnel and it is considered as a part of the LHC programme [8]. Parameters of electron and proton beams for this option are given in Table I. It is seen that center of mass energy $\sqrt{s_{ep}} = 1.37$ TeV and luminosity $L_{ep} = 1.2 \times 10^{32}$ cm^{-2}s^{-1} will be achieved.

Let us consider the use of e-linac instead of e-ring with ~ 27 km circumference. With $E_e = 67.3$ GeV and $P_e = 34.5$ MW and nominal LHC proton beam parameters ($N_p = 1.1 \times 10^{11}$, $\varepsilon_p = 0.5$ nm, $\beta_p^* = 0.5$ m [12]) we obtain for linac-ring option $L_{ep} = 1.1 \times 10^{31}$ cm^{-2}s^{-1} according to Eq. (1). If one choose the THERA (TESLA+HERA based *ep* collider proposal) proton beam parameters [13], namely, $N_p = 10^{11}$, $\varepsilon_p^N = 10^{-6}$ m and $\beta_p^* = 10$ cm the luminosity for "ideal" e-linac becomes $L_{ep} = 1.9 \times 10^{32}$ cm^{-2}s^{-1}.

Concerning the "real" e-linac technologies we consider TESLA and CLIC proposals. Parameters of the TESLA (THERA option [13]) and CLIC [14] e-beams are given in Table II. It is seen from Table III that in the TESLA case one can use all e-bunches, whereas only $\sim 3\%$ of the CLIC e-bunches will collide with the LHC proton bunches. (Let us mentioned that superbunch option for the LHC could give opportunity to utilize all CLIC bunches [15] but this opportunity requires a radical modification of whole LHC stages from injector to main ring). With nominal LHC parameters we obtain $L_{ep} = 1.9 \times 10^{30}$ cm^{-2}s^{-1} for "TESLA" and $L_{ep} = 1.4 \times 10^{28}$ cm^{-2}s^{-1} for "CLIC"

TABLE I

Parameters for standard type LHC *ep* collider [6].

Electron beam parameters	
Energy E_e (GeV)	67.3
Bunch population, N_e	6.4×10^{10}
Emittance, ε_e (nm)	9.5/2.9
Beta functions, β_{xe}/β_{ye}, (m)	0.85/0.26
Beam–beam tune shifts, $\Delta Q_x/\Delta Q_y$	0.027/0.027
Radiation power W [MW]	34.5
Proton beam parameter	
Energy E_p (TeV)	7
Bunch population, N_p	10^{11}
Emittance, ε_p (nm)	0.5
Beta functions, β_{xp}/β_{yp}, (m)	16/1.50
Beam–beam tune shifts, $\Delta Q_x/\Delta Q_y$	0.0032/0.0010
Collider parameters	
Center of mass energy, $\sqrt{s}$ (TeV)	1.37
Luminosity (10^{32} cm^{-2}s^{-1})	1.2

TABLE II

Nominal parameters of the TESLA and CLIC *e*-beams.

	TESLA	CLIC
Accelerating gradient MeV/m	23.4	150
Bunch spacing, τ_e (ns)	211.37	0.66
Number of bunches, n_{b}	5600	154
Repetition rate, f_{rep}, (Hz)	5	200
Number of electrons per bunch, N_e (10^{10})	2	0.4

(see Table III). With THERA like modification of the LHC proton beam, the luminosity values become $L_{ep} = 3.3 \times 10^{31}$ cm^{-2}s^{-1} and 2.3×10^{29} cm^{-2}s^{-1}, respectively (see Table IV). It is seen that a factor of ~ 3.5 for TESLA technology and a factor of ~ 500 for CLIC technology are needed in order to achieve a luminosity $L_{ep} = 1.2 \times 10^{32}$ cm^{-2}s^{-1}.

TABLE III

Main parameters of "TESLA"-LHC and "CLIC"-LHC colliders with nominal LHC beam.

	TESLA	CLIC
Effective linac length (km)	2.88	0.45
Bunch spacing, τ_e (ns)	211.37	0.66
τ_p/τ_e ($\tau_p = 25$ ns)	0.118	37.88
Effective bunch number, $n_{\rm b}^{\rm eff}$	5600	5
Bunch population, N_p	1.1×10^{11}	1.1×10^{11}
Beta function, β_p^* (m)	0.5	0.5
Emittance, ε_p (nm)	0.5	0.5
Luminosity, L_{ep} (cm^{-2}s^{-1})	1.9×10^{30}	1.4×10^{28}

TABLE IV

Main parameters of "TESLA"-LHC and "CLIC"-LHC with THERA like upgrade of the LHC proton beam parameter.

	TESLA	CLIC
Bunch population, N_p	10^{11} (5×10^{11})	10^{11} (5×10^{11})
Beta function, β_p^* (cm)	10	10
Normalized emittance, ε_p^N (μm)	1	1
Beam–beam tune shift, ΔQ_p	0.0024	0.0005
Disruption, D	12 (60)	12 (60)
Luminosity, L_{ep} (cm^{-2}s^{-1})	3.3×10^{31} (1.6×10^{32})	2.3×10^{29} (1.2×10^{30})

Because of 7 times higher proton beam energy comparing to the HERA the number of protons in LHC bunches can be essentially enlarged. For example, the LHC beam lifetime is ~ 5 h for $N_p = 5\times10^{11}$ and $\varepsilon_p^N = 10^{-6}$ m. Therefore, luminosity $L_{ep} = 10^{32}$ cm^{-2}s^{-1} can be achieved with TESLA technology. Radical modification of electron beam is necessary in the case of CLIC technology. For example, N_e can be enlarged by the factor of 2.5 [16] (the beam–beam tune shift, Eq. (3), permits the factor ~ 6). In addition, the effective collision frequency can be enlarged by factor 10 due to corresponding increase of the number of bunch trains per RF pulse a la CLICHÉ [17]. Remaining factor 4 may be provided by "dynamic focusing" [18].

To summarize, using TESLA and CLIC like electron linacs with active lengths ~ 2.9 km and ~ 0.45 km respectively, one can obtain the same center of mass energy in the case of ~ 27 km electron ring. Concerning the luminosity, "moderate" upgrade of TESLA and LHC beams could give opportunity to achieve $L_{ep} = 10^{32}$ cm^{-2}s^{-1}, whereas "radical" upgrades of e-beam is needed for CLIC.

4. The VLHC based *ep* collider

The standard type ep collider based on VLHC assumes a construction of 180 GeV e-ring in the VLHC tunnel [9]. In this case length of the ring is 531 km, radiated power loss for electron beam is 50 MW, center of mass energy is 6 TeV and luminosity is 1.4×10^{32} cm^{-2}s^{-1} [9]. Main parameters of this machine are listed in Table V.

Concerning linac-ring option, with $E_e = 180$ GeV and $P_e = 50$ MW and THERA-like upgrade of the VLHC proton beam parameters $N_p = 10^{11}$, $\varepsilon_p^N = 10^{-6}$ m and $\beta_p^* = 10$ cm, according to Eq. (1) we obtain $L_{ep} = 7.3 \times 10^{32}$ cm^{-2}s^{-1} for "ideal" e-linac. The active lengths are 7.7 km and 1.2 km for TESLA and CLIC like electron linacs, respectively.

Main parameters of "TESLA"-VLHC and "CLIC"-VLHC options with THERA like upgrade of the VLHC proton beam are given in the Table VI. It is seen that the needed luminosity is achieved with nominal TESLA parameters, whereas a factor of ~ 70 is required for the CLIC case. Possible solutions for the latter case are presented in the previous section.

TABLE V

Parameters for standard type VLHC ep collider [9].

Electron beam parameters	
Energy E_e (GeV)	180
Bunch population, N_e	10.1×10^{10}
Beam–beam tune shifts, $\Delta Q_x/\Delta Q_y$ (10^{-3})	6.1/2.9
Radiation power W [MW]	50
Proton beam parameter	
Energy E_p (TeV)	50
Bunch population, N_p	12.5×10^{10}
Beam–beam tune shifts, $\Delta Q_x/\Delta Q_y$ (10^{-3})	4/0.3
Collider parameters	
Center of mass energy, $\sqrt{s}$ (TeV)	6
Luminosity (10^{32} cm^{-2}s^{-1})	1.4
Circumference, (km)	531

TABLE VI

Main parameters of "TESLA"-VLHC and "CLIC"-VLHC with THERA-like upgrade of the LHC proton beam parameter.

	TESLA	CLIC
Bunch population, N_p	10^{11}	10^{11}
Beta function, β_p^* (cm)	10	10
Normalized Emittance, ε_p^N (μm)	1	1
Beam–beam tune shifts, ΔQ_p	0.0024	0.0005
Disruption, D	31.8	31.8
Effective linac length (km)	7.69	1.2
Bunch spacing, τ_e (ns)	211.37	0.66
τ_p/τ_e ($\tau_p = 19$ ns)	0.089	28.78
Luminosity, L_{ep} (cm^{-2}s^{-1})	2.3×10^{32}	2×10^{30}

5. Physics example: pair production of heavy quarks

The physics search potential of an $\sqrt{s} = 1$ TeV *ep* collider is extensively analyzed during 2 years THERA study [13] (see also [12–27]. Here we consider in details one example, namely gluon distributions, which is very important for Higgs physics at the LHC, because gluon fusion is the dominant channel for Higgs boson production at hadron colliders.

Measurements of the heavy quarks produced in the process of photon–gluon fusion (PGF) can be used for the direct reconstruction of the gluon structure of the proton [28]. Fig. 1 shows the differential cross sections $d\sigma/d\log_{10} x_g$ (x_g denoting the gluon fractional moment in the proton) for charm and beauty produced in PGF at HERA, THERA, QCD Explorer and Linac–VLHC. The cross sections were calculated within NLO QCD [29] for $Q^2 < 1$ GeV^2. The GRV98 [30] parameterization was used for the proton structure function. The parameterization was artificially extended to the range $Q^2 > 10^6$ GeV^2 to cover the full-scale range of the Linac–VLHC collider. The increase of the electron beam energy will provide an opportunity to probe at THERA one order of magnitude smaller x_g values with respect to those at HERA. The kinematics limits of the x_g measurements at THERA are 10^{-5} and 10^{-4} for charm and beauty production, respectively. Similar statement is valid for QCD Explorer, which has approximately the same center of mass energy as THERA. Linac–VLHC will give opportunity to explore an order lower value for x_g. However, to be sensitive to the x_g values around the kinematics limits one will need to tag heavy quarks in the very backward (electron) direction.

Plot (a) and (b) in Fig. 2 show the predictions for THERA with $E_e =$ 250 GeV and $E_p = 1$ TeV imposing additional cuts $\theta^{c,b} < 179°$, $\theta^{c,b} < 175°$ and $\theta^{c,b} < 170°$. Only charm quarks with $\theta^c > 175°$ demonstrate sensitivity to the as yet unexplored range $2 \times 10^{-5} \leq x_g < 10^{-4}$. Similar plots for QCD Explorer are presented in Fig. 3. Due to a little bit higher center of mass energy and especially larger asymmetry of beam energies one will be able to explore $10^{-5} < x_g < 10^{-4}$ using charm quarks with $\theta^c < 175°$. Moreover, comparison of Figs. 2(a) and 3(b) show that the x_g region, which can be explored by c quarks with $\theta^c < 175°$ at THERA, is covered by b quarks with $\theta^b < 175°$ at QCD Explorer. Approximately 40 times larger cross-section for $\overline{c}c$ pair production at THERA covering to $\overline{b}b$ pair production at QCD Explorer can be compensated by higher luminosity of the latter one. Linac–VLHC will give opportunity to explore $10^{-5} < x_g < 10^{-4}$ using beauty quarks with $\theta^c < 175°$ as seen from Fig. 4(b), whereas charm quarks are sensitive up to an order lower $x_g \approx 10^{-6}$ (Fig. 4(a)).

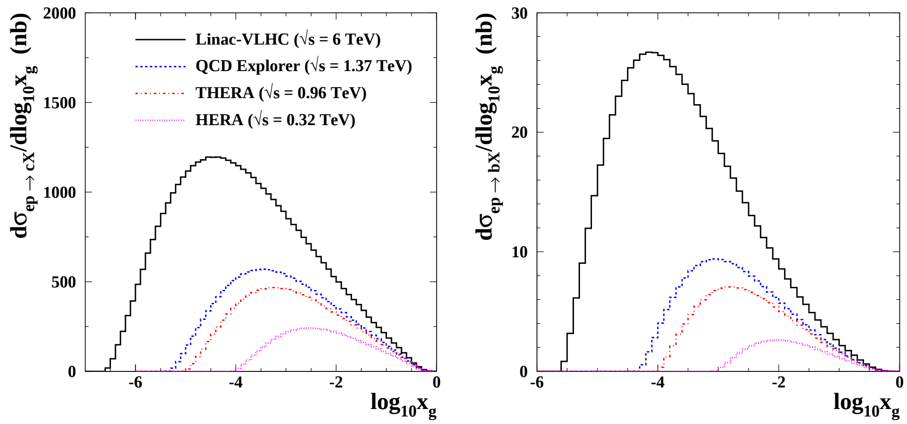

Fig. 1. The differential cross-section $d\sigma/d\log_{10}x_g$ for charm (left) and beauty (right) produced in the process of γ^*g fusion. Solid, dash-dotted, dashed and dotted curves correspond to Linac–VLHC, QCD Explorer, THERA and HERA, respectively.

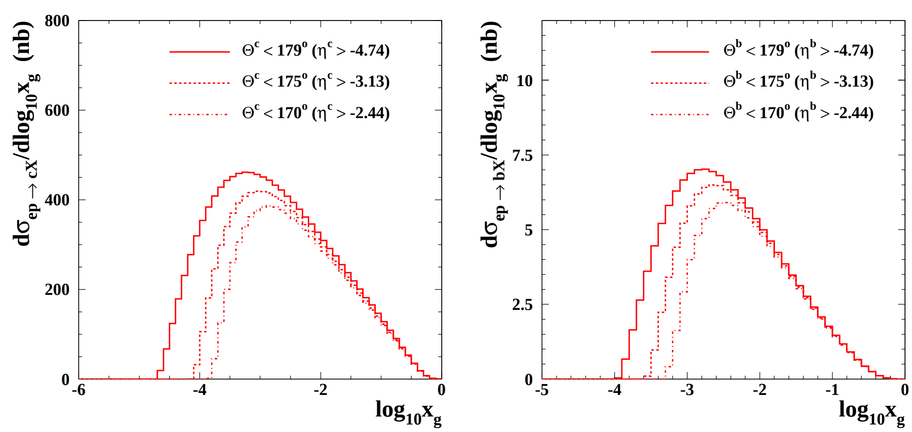

Fig. 2. The prediction for the THERA with additional cut $\theta^{c,b}< 179°$ (solid curves) $\theta^{c,b}< 175°$ (dashed curves) and $\theta^{c,b}< 170°$ (dotted curves).

Total cross-section for charm and beauty production at $\sqrt{s} = 1$ TeV are $\approx$ 2 μb and 25 nb, respectively. As a result, even $L = 10^{30}$ cm^{-2}s^{-1} will provide 2×10^7 $\bar{c}c$ and 2×10^5 $\bar{b}b$ pair per working year (10^7 s). Therefore, linac-ring type *ep* colliders will give opportunity to perform detailed investigation of gluon distribution in proton.

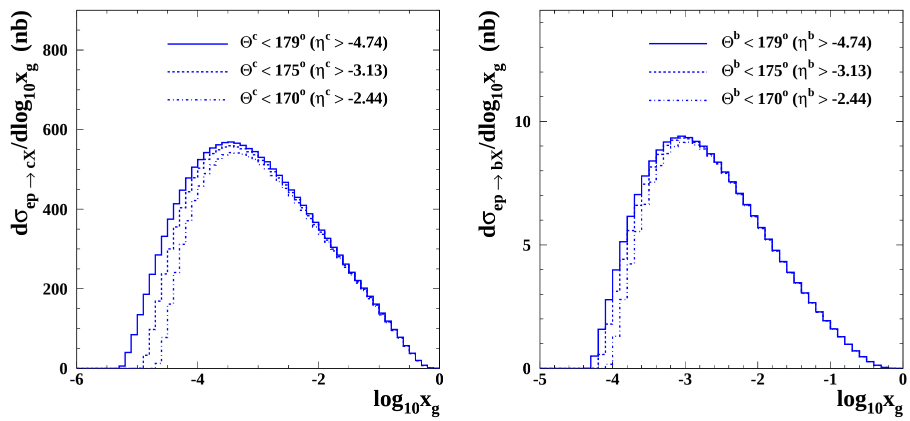

Fig. 3. The same as Fig. 2 but for the QCD Explorer.

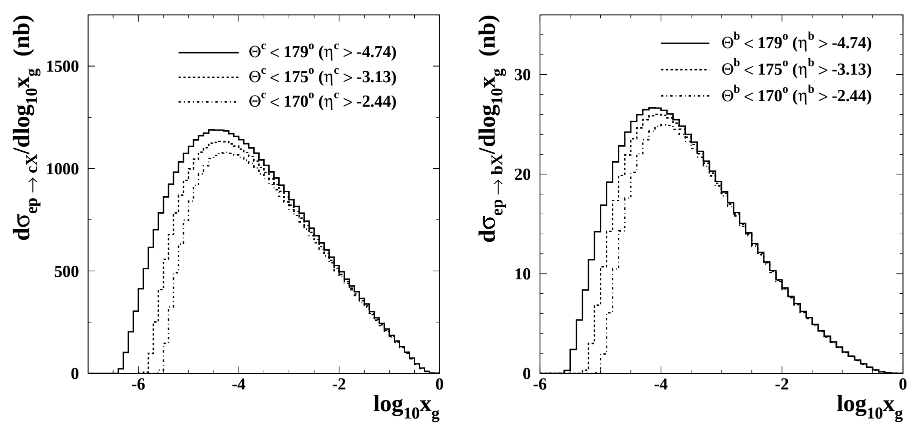

Fig. 4. The same as Fig. 2 but for Linac–VLHC.

6. QCD-E *versus* LHeC

Recently, Large Hadron Electron Collider (LHeC) is proposed, in which a 70 GeV electron (positron) beam in the LHC tunnel is in collision with one of the LHC hadron beams [31].

Main parameters of the LHeC lepton and proton beams are presented in Table VII. Center of mass energy and expected luminosity are $\sqrt{s_{ep}} = 1.4$ TeV and $L_{ep} = 10^{33}$ cm^{-2}s^{-1}, respectively. However, construction of an additional e-ring in the LHC tunnel might cause a lot of technical problems: an example is inevitable removing of the LEP from the tunnel in order to assemble the LHC. In any case, LHC could not operate during the installation of e-ring. For these reasons, alternative linac-ring type ep option for the LHC should be considered seriously.

TABLE VII

Main parameters of the LHeC beams [31].

	Leptons	Protons
Beam energies, GeV	70	7000
Particles per bunch, 10^{10}	1.04	17
Bunch spacing, ns	25	25
Horizontal emittance, nm	25.9	0.5
Vertical emittance, nm	5	0.5
Horizontal β at IP, cm	3.77	180
Vertical β at IP, cm	4.44	50
Energy loss per turn, GeV	0.676	6×10^{-6}
Radiated energy, MW	50	0.003

The most transparent expression (in practical units) for the luminosity of linac-ring type ep colliders is [32]:

$$Ł = 4.8 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \frac{n_p}{10^{11}} \frac{10^{-6}\,\mathrm{m}}{\varepsilon_p} \frac{\gamma_p}{1066} \frac{10\,\mathrm{cm}}{\beta_p} \frac{P_e}{22.6\,\mathrm{MW}} \frac{250\,\mathrm{GeV}}{E_e}\,, \qquad (5)$$

where P_e denotes electron beam power, which is taken equal to radiation power of corresponding e-ring. With $E_e = 70$ GeV, $P_e = 50$ MW and LHC proton beam parameters from the Table VII one obtain $L_{ep} = 2.4 \times 10^{31}$ cm^{-2}s^{-1} for linac-ring option. If one choose the THERA proton beam parameters [13], namely, $n_p = 10^{11}$, $\varepsilon_p^N = 10^{-6}$ and $\beta_p^* = 10$ cm, the luminosity for "ideal" e-linac becomes $L_{ep} = 2.6 \times 10^{32}$ cm^{-2}s^{-1}. An additional factor 3–4 can be provided using dynamical focusing [18]. Therefore, QCD Explorer could provide for ep option the same luminosity as LHeC, in principle.

To summarize, using TESLA and CLIC like electron linacs with active length ~ 2.9 km and ~ 0.45 km, respectively, one can obtain the same center of mass energy as in the case of ~ 27 km electron ring. Concerning the luminosity, "moderate" upgrade of TESLA and LHC beams could give opportunity to achieve $L_{ep} = 10^{32}$ cm^{-2}s^{-1}, whereas "radical" upgrades of e-beam is needed for CLIC. Obviously, design of a "dedicated" linac will essentially improve QCD-E parameters.

7. Conclusion

Lepton hadron colliders with $\sqrt{s} > 1$ TeV are necessary both to clarify fundamental aspects of the QCD part of the Standard Model and for adequate interpretation of experimental data from multi-TeV hadron colliders. A construction of an additional e-ring in the LHC and VLHC tunnels might cause a lot of technical problems. Linacs give opportunity to obtain the same e-beam energy with much shorter lengths. The development of the resolution power of the experiments exploring the inner structure of matter over time from Rutherford experiment to CLIC–VLHC is illustrated in Fig. 5 [33].

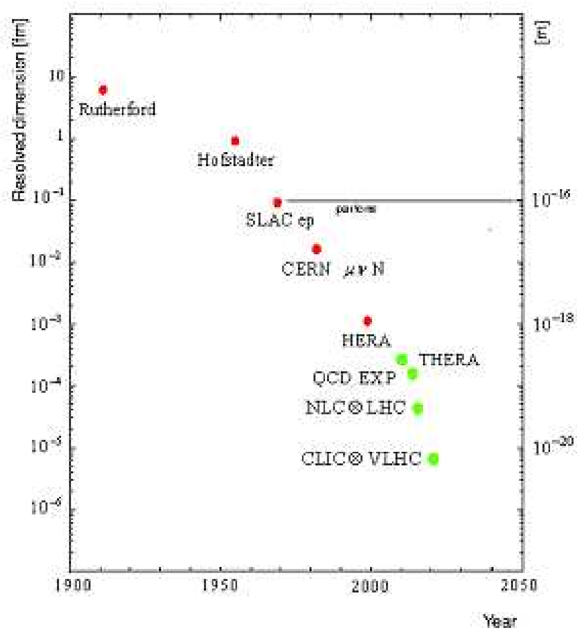

Fig. 5. The development of the resolution power of the experiments exploring the inner structure of matter over time from Rutherford experiment to CLIC–VLHC.

Today, there are two realistic proposals, namely, QCD Explorer and LHeC. Both QCD-E and LHeC will give opportunity to achieve sufficiently high luminosity to explore crucial aspects of the strong interactions. Whereas

LHeC is based on the more familiar approach (we have nice experience from the HERA), QCD-E has a number of advantages:

— additional γp, γA and FEL γA options,

— electron beam energy can be expanded by increasing linac length, whereas synchrotron radiation blocks this road for LHeC,

— minimal influence on the LHC tunnel.

The main goal of both QCD-E and LHeC proposals is to clarify fundamental aspects of strong interactions. Their potential for the BSM physics search is restricted by center of mass energy. Therefore, very high luminosity is not so important. In our opinion γA option of the QCD-E will provide crucial information on QCD dynamics at small x_g in nuclear medium.

This work is partially supported by the Turkish State Planning Organization under the grand no 2002K120250.

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